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Comparing energy efficiency of USB at full-speed and high-speed rates

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White Paper

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1. Introduction

This document examines power consumption per bit of USB devices at full-speed (12 Mbit/s) and high-speed (480 Mbit/s) data transfer rates, and compare their energy efficiency.

The system-level environment is not taken into account during the tests. This document focuses on device parameters.

2. Theoretical calculation of current in full-speed

The average drive current for a USB data line is the mean current used to charge or discharge the total capacitance (C_{line}) of the line. This includes both lumped capacitances and the transmission line's distributed capacitance.

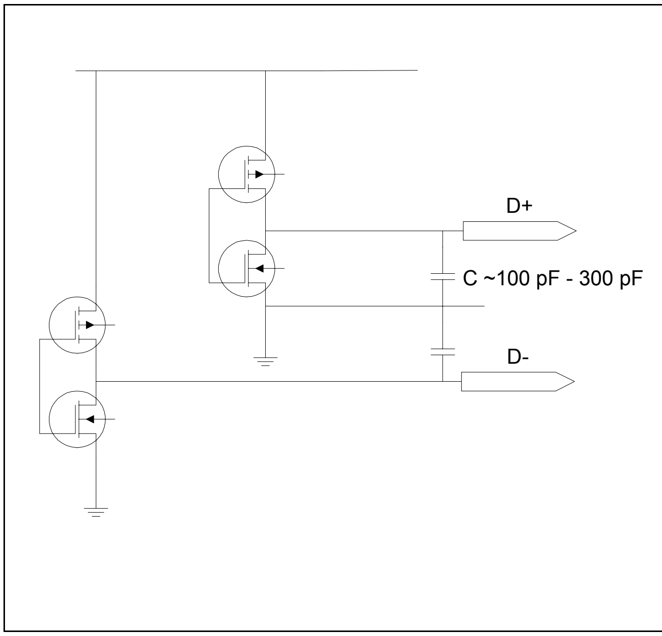


Figure 2-1: Full-speed transceiver (transceiver part)

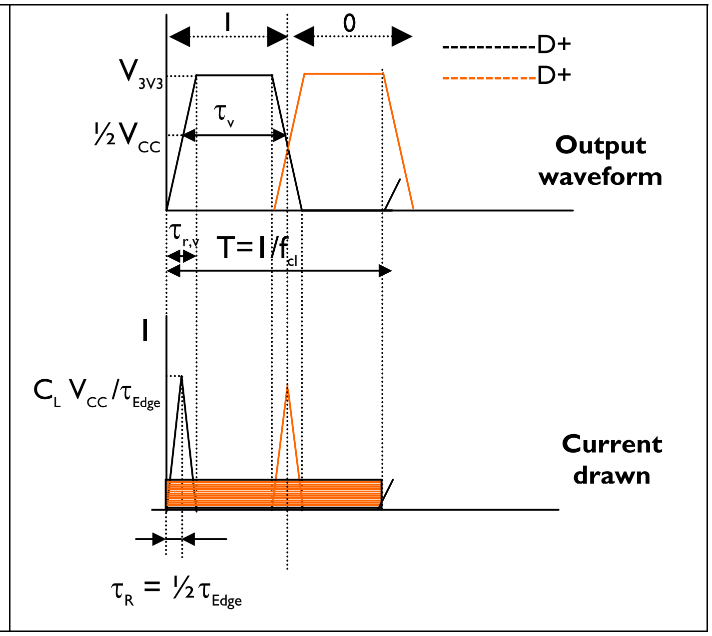


Figure 2-2: Output waveform and current drawn

The average drive current is derived by the integration of two-peak currents (one from the D+ data line and the other from the D- data line) over a period of two full-speed bit times .

When one data line draws current from the power rail, the other line returns current to ground (can be ignored). This is because USB transmitters use CMOS push-pull drivers.

The data lines when taken together form a complete circuit that moves charges from the supply to ground. Therefore, the current through the power supply of the transmitter is the same as the drive current for **one** data line.

$$I_{peak} = C\frac{dV}{dt}$$

Where *C* is the line capacitance of the USB cable.

dV/dt is the change in voltage with respect to time. The *Universal Serial Bus Specification Rev. 2.0* allows a range of 4 ns to 20 ns.

In summary, the average current derived will be:

$$\bar{I} = \frac{C_{line}\Delta V}{2\bar{T}}$$

Where T is 83.3 ns.

ΔV ranges from 2.5 V to 3.6 V.

C_{line} can be between 10 pF to 1070 pF approximately, depending on the length of the USB cable and the construction of the devices attached to it. Typical line loads measured are in the range of 70 pF for a 1-m cable to 300 pF for a 5-m cable. An average of 150 pF will be used, which includes an average 120 pF capacitance for a 1.5-m cable plus 30 pF parasitic board capacitance.

Therefore, the typical current drawn is calculated as approximately 2.5 mA, assuming a 3.3 V swing and continuous data toggling.

The average power dissipation for a full-speed transmitter will be:

$P = I_{average} \times 3.3\ V$ = 15 mW (Under the same conditions as the currents specified earlier.)

3. High-speed USB signaling

A high-speed USB device using the following scheme has a single current source that is switched between D+ and D-. The output of the current source is:

$$I = \bar{I} = V_{line}\left(\frac{1}{R_{parallel\ resistor}} + \frac{1}{Z_{line}}\right)$$

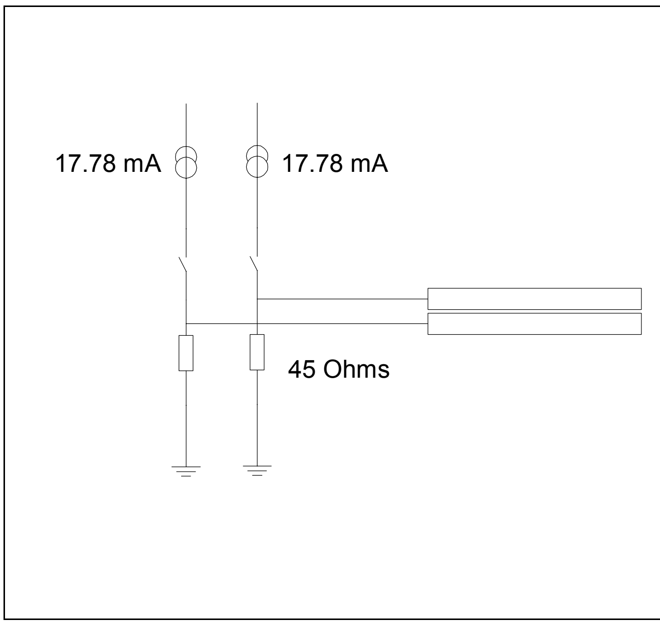


Figure 3-1: High-speed transceiver

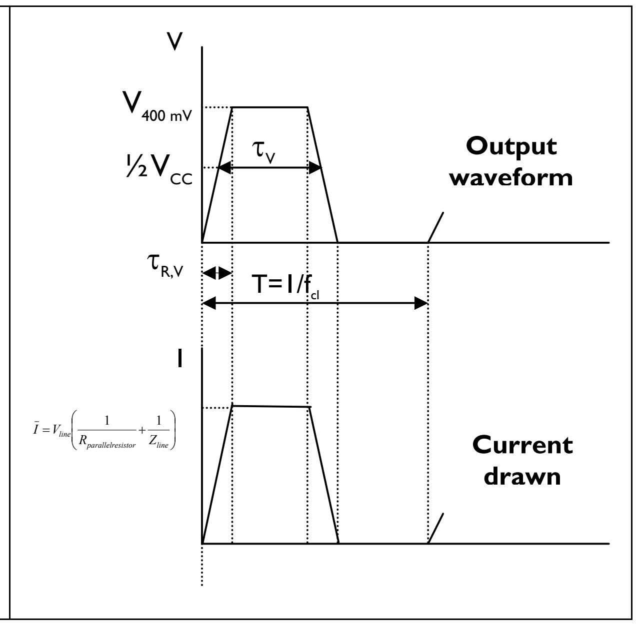


Figure 3-2: Output waveform and current drawn

For an ideal 45 Ω line and 45 Ω termination, a 17.8-mA drive is required to bring the line 400 mV above ground. Half of this current is immediately sunk into the termination of the transmitter and the other half enters the transmission line.

The current required to drive a data line is the same as that required to drive the port because the current source is switched between the data lines. The actual amount of current that enters each leg of the current divider, however, depends on how well the impedance of the data line matches the parallel termination. For example, a 38.25 line can accept up to 9.65 mA and a 51.75 line can accept up to 8.22 mA with a 17.8 mA current source and a 1% termination resistor. The line voltages can remain stable for longer than the round-trip propagation time of the cable in case of short cables. In this case, the line current normally falls back to the mean because the termination resistor at the far-end of the cable is likely to be better matched than the terminator at the near-end of the cable.

4. Full-speed vs. high-speed

On a per port basis, the high-speed USB signaling compares reasonably well with a typical full-speed USB configuration.

Parameter	Nominal full-speed	Typical high-speed
Peak port drive current	40 mA	17.8 mA
Peak port power	40 mA x 3.3 V = 132 mW	7.5 mW
Average port drive current	2.9 mA	17.8 mA
Average port power	9.6 mW	7.1 mW

5. Test methodology

In this investigation, it is important to understand the power required to transmit or receive in the high-speed or full-speed mode; especially, in the area of embedded handheld devices in which the energy stored in the battery is required to transmit or receive.

The test methodology setup is to investigate energy needed both in the high-speed and full-speed modes in a real environment. Therefore, the setup is a mass storage (IDE drive) and ThumbDrive® connected to a laptop to perform 3.5-MB file read and write transfers.

In Figure 5-1, the average power is obtained from the measurement of voltage and current in three different cases under file read and write scenarios.

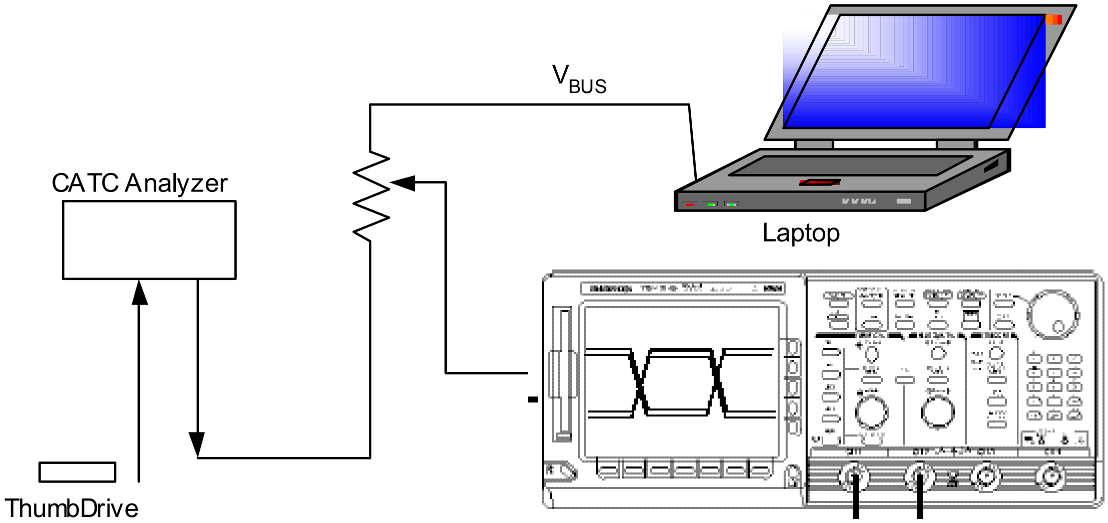


Figure 5-1: Measurement setup

The current measurement is categorized into four physical states present on the USB bus traffic:

- Plug-in state—enumeration
- Idle state—not transmitting
- Read or write file transfer state
- Suspend state.

An average scenario would be 2% for the enumeration time, 10% for the idle state time, 80% for the transfer state time, and the remaining percentage for the suspend state time.

Philips Semiconductors has chosen to compare efficiency based on the read or write file transfer state because the rest of the USB states are highly dependent on the implementation method for the product.

Therefore, the average power, which is the ratio of the energy to transfer data in full-speed and high-speed, will be calculated as:

Energy = Average power / throughput

Where *throughput* is the percentage of *payload data* x *data rate* [High-speed (480 Mbit/s) or full-speed (12 Mbit/s)].

6. Assumption

The measurement setup is based on a mass storage application. The overhead may be different if a different application is used. For instance, printers may have less overhead.

The result of this measurement is also subjected to the USB host, device hardware, efficiency of the host stack, device driver, and so on.

7. Current comparison

Table 7-1 shows the operating current comparison between various types of USB devices.

Table 7-1: Operating current measurement

USB device	Full-speed		High-speed	
	Idle	RW	Idle	RW
ISP1581 mass storage	116 mA	118 mA	145 mA	151 mA
Trek® USB ThumbDrive	22 mA	27 mA	Not applicable	Not applicable
ISP1583 mass storage	50 mA	54 mA	66.2 mA	70 mA
Maxtor® USB hard disk	116 mA	126 mA	197 mA	201 mA

The current measurement in Table 7-1 is taken using the normal DC current meter. The current reading includes USB controller and other processing logic (8051) on the PCB board. This measurement is compared with the average current taken using a digital scope (capture the voltage drop across through the 1 Ω precision resistor); see Appendix C: Current measurements.

The average current consumption for a full-speed device is close to the theoretically calculated value of 4 mA. In the case of high-speed devices, however, a difference of 4 mA is seen, probably because averaging was done over a longer time frame. The difference is more obvious using digital scope—it can reach close to 17 mA.

8. Transfer rate performance

The transfer rate measurement is then compared based on 4-MB file transfers to and from the PC by using the hard disk drive (HDD) test bench software.

Table 8-1: Throughput performance

USB device	Full-speed		High-speed	
	Read	Write	Read	Write
M-Systems® DiskOnKey® Classic 2.0 (ISP1581)	962 KB	824 KB	3197 KB	1074 KB
Hi-Speed USB (USB 2) Sony® Memory Stick®	610 KB	470 KB	842 KB	602 KB
ISP1581 mass storage[1]	939 KB	966 KB	10921 KB	12487 KB
Maxtor® USB hard disk	959 KB	939 KB	21787 KB	23812 KB
Tektronix® USB key	955 KB	886 KB	Not applicable	Not applicable
Trek 2000® USB ThumbDrive®	462 KB	203 KB	Not applicable	Not applicable
ISP1583 mass storage[1]	959 KB	939 KB	10921 KB	11409 KB

[1] The mass storage kit for the ISP1581 and the ISP1583 use the Maxtor hard disk model 'DiamondMax™ Plus 8' 20 GB ATA133.

Theoretically, the performance increase from USB full-speed to high-speed should be a factor of 40 times. From the measured comparison results shown in Table 8-1, however, the performance increase ranges from 3.5 times for M-Systems DOK 2.0 to 20 times for Maxtor USB hard disk.

Using CATC USB bus traffic analysis (see Appendix B: CATC traffic and Appendix C: Current measurements), the difference in speed can be identified mainly because of the processing time required by the microcontroller to transfer data from the flash memory to the USB controller's buffer. Besides this hardware restriction, the total time for the file transfer activity to complete is sometimes captured as almost identical when comparing high-speed and full-speed transfer modes. This is because of the OS polling for status in the case of removable storage devices, which is time random in nature.

The time taken for a read or write data transfer can be further divided into:

- Time to transfer 64 bytes or 512 bytes of data
- Time to fill the buffer
- Time to respond to Command Status Wrapper (CSW).

Table 8-2 summarizes the timing data gathered from various devices.

Table 8-2: Timing data

USB device	Full-speed (64-byte endpoint)			High-speed (512-byte endpoint)		
	Time to transfer a 3.4 MB file	**Time to fill the USB buffer to transfer next 64 bytes at 46 µs**	**Time to respond to CSW**	**Time to transfer a 3.5-MB file**	**Time to fill the USB buffer to transfer next 512 bytes at 9 µs**	**Time to respond to CSW after a 65-KB data transfer**
Trek USB ThumbDrive (PDIUSBD12)	7.5 sec	35 µsec	Not available	Not applicable	Not applicable	Not applicable
ISP1581 mass storage	3.5 sec	8 µsec	1623 µsec	277 msec	25 µsec to 31 µsec	240 µsec
Maxtor mass storage	3.5 sec	9 µsec	1789 µsec	133 msec	3 µsec	151 µsec
ISP1583 mass storage	3.5 sec	9 µsec	1351 µsec	300 msec	25 µsec to 31 µsec	325 µsec

As can be seen in Table 8-2, the 'down time' for the Maxtor USB drive is extremely low as compared to the ISP1581 (31 µsec). The longest record captured for Maxtor is 19 µsec, which is equivalent to 50 MHz of transfer rate between the USB and memory. This is probably because of efficient data transfer architecture used.

Table 8-3 summarizes the energy difference for various devices.

Table 8-3: Energy difference comparison

Energy	ISP1581	ISP1583	Maxtor hard disk	PDIUSBD12
Energy taken for high-speed to transfer 3.5 MB of file	(277 msec x 151 mA x 5 V) / 3.5 MB = 59 nJoule/byte	(300 msec x 70 mA x 5 V) / 3.5 MB = 30 nJoule/byte	(133 msec x 201 mA x 5 V) / 3.5 MB = 38 nJoule/byte	Not applicable
Energy taken for full-speed to transfer 3.5 MB of file	(3.5 sec x 118 mA x 5 V) / 3.5 MB = 590 nJoule/byte	(3.5 sec x 54 mA x 5 V) / 3.5 MB = 270 nJoule/byte	(3.5 sec x 126 mA x 5 V) / 3.5 MB = 630 nJoule/byte	(7.5 sec x 28 mA x 5 V) / 3.5 MB = 300 nJoule/byte
Energy difference	10 times	9 times	16.5 times	7.9 to 105 times[1]
Energy comparison based on ideal condition (comparison for one buffer transfer)				

Energy	ISP1581	ISP1583	Maxtor hard disk	PDIUSBD12
Energy/byte taken for high-speed to transfer 512 bytes of file	(9 µsec x 151 mA x 5 V) / 512 bytes = 13.2 nJoule/byte	(9 µsec x 70 mA x 5 V) / 512 bytes = 6.1 nJoule/byte	(9 µsec x 201 mA x 5 V) / 512 bytes = 17.6 nJoule/byte	Not applicable
Energy taken for full-speed to transfer 64 bytes of file	(46 µsec x 118 mA x 5 V) / 64 bytes = 424 nJoule/byte	(46 µsec x 54 mA x 5 V) / 64 bytes = 194 nJoule/byte	(46 µsec x 126 mA x 5 V) / 64 bytes = 452 nJoule/byte	(46 µsec x 28mA x 5 V) / 64 bytes = 100 nJoule/byte
Energy difference	32 times	32 times	25.7 times	5.7 to 16.4

[1] When comparing the ISP1583 IDE mass storage kit (high-speed) and Maxtor hard disk (high-speed) to full-speed PDIUSBD12.

Energy difference in ideal cases

The Root Mean Square (RMS) current for full-speed over two bits will be approximately 2.9 mA. (*Idc = Co x V / 167 nsec*, given *Co* = 150 pF).

Average power = (*2.9 mA x 3.3 V*) = 9.6 mW

The RMS current for high-speed over 1 bit will be approximately 17.8 mA. (*Idc = 400 mV/22.5 Ω*).

Average power = (*17.8 mA x 400 mV*) = 7 mW

Table 8-4: Energy comparison based on ideal condition

Energy	Enumeration	Idle	File transfer	Suspend
Energy taken for high-speed to transfer 512 bytes of file	Not applicable	Not applicable	(9 µsec x 7 mW) / 512 bytes = 123 pJoule/byte	Not applicable
Energy taken for full-speed to transfer 64 bytes of file	Not applicable	Not applicable	(46 µsec x 9.6 mW) / 64 bytes = 7 nJoule/byte	Not applicable
Energy difference			57 times	

9. Conclusion

The energy difference (an increase by 57 times if high-speed is used) is based on theoretical calculation when converting from full-speed to high-speed design. In practice, however, the maximum saving achievable is up to 32 times when the packet transfer configuration is compared. The reduction is mainly contributed by the increase in current consumption for high-speed SIE engine in which its internal system is running at 480 MHz clock speed. The 32 times efficiency is further reduced depending on the type of hardware architecture adopted in the design. Therefore, the final improvement will range from approximately 10 times to 15 times only.

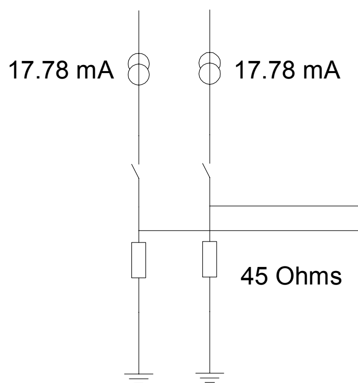
10. References

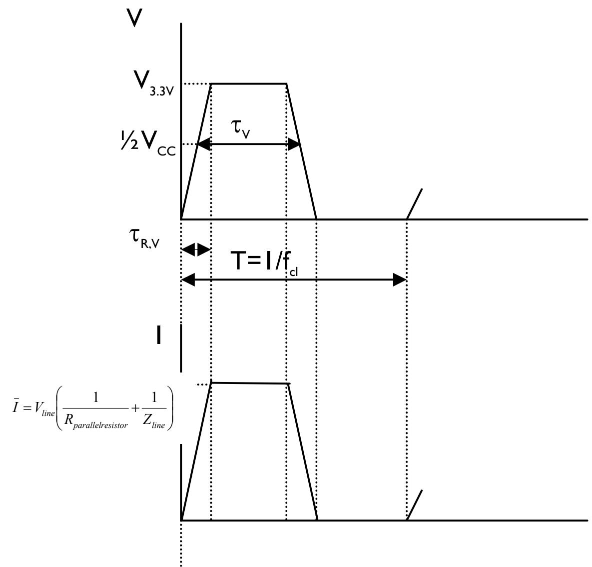
- *Universal Serial Bus Specification Rev. 2.0*
- *ISP1581 Hi-Speed Universal Serial Bus interface device* data sheet
- *ISP1582 Hi-Speed Universal Serial Bus interface device* data sheet
- *ISP15831 Hi-Speed Universal Serial Bus interface device* data sheet
- *PDIUSBD12 USB interface device with parallel bus* data sheet.

Appendix A: Current comparison—high-speed vs. full-speed

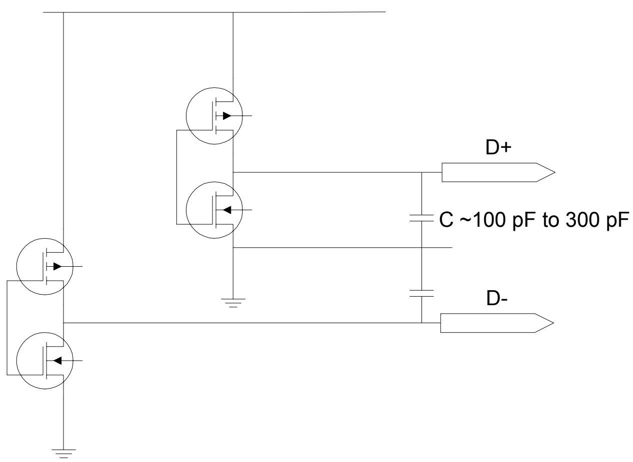
Theoretically, the full-speed drive current consumption should depend on the capacitance of the USB cable. The largest current swing (*Ipeak*) can go up to 40 mA. Only 4 mA RMS is, however, observed. This could be because most of the switching current is provided by the on-board decoupling capacitors closer to the USB transceiver as current is taken through V_{BUS}. Using the formulae (Section 2), the average current can be visualized as the red block as shown in the diagram on the following page.

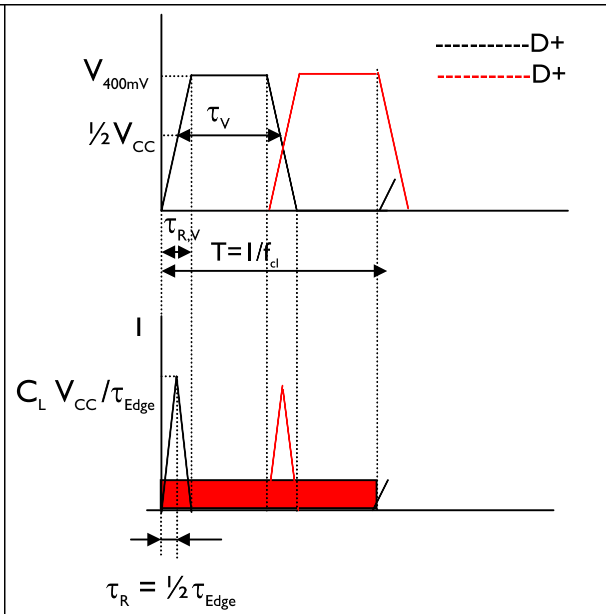
High-speed





Full-speed

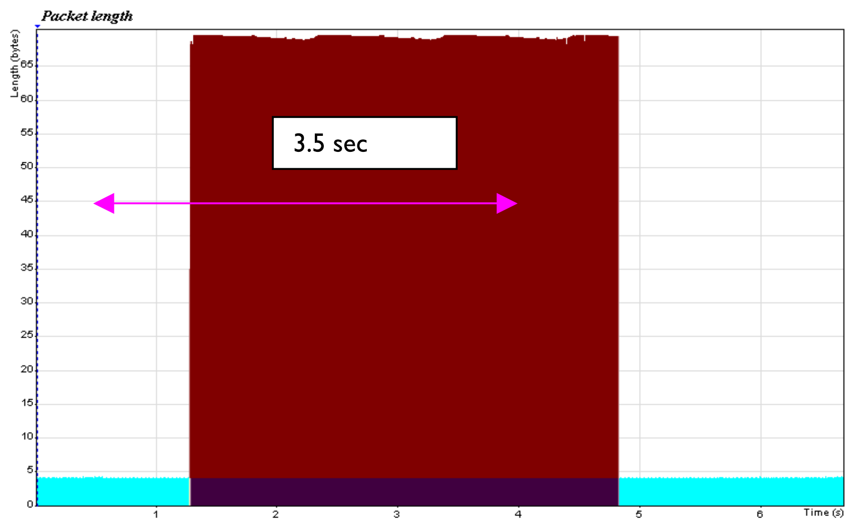
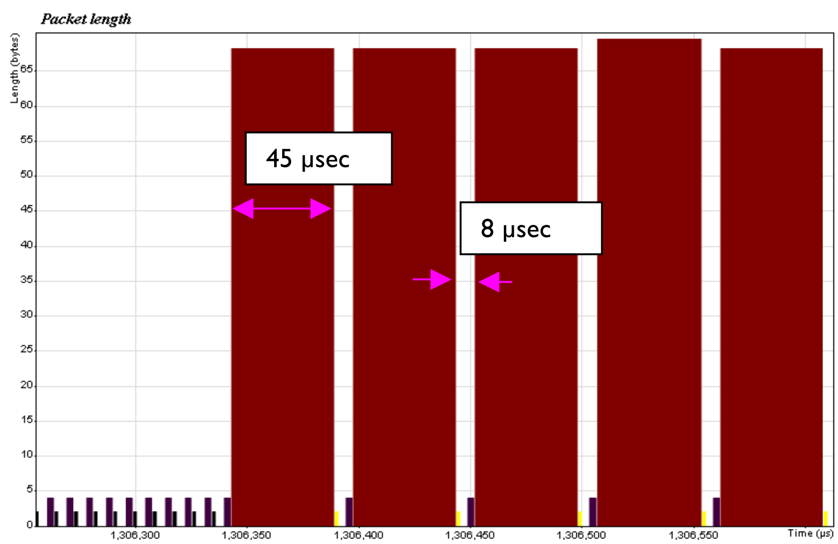

D+
C ~100 pF to 300 pF
D-


-----------D+
-----------D+
V400mV
½VCC
τV
τR,V
T=1/fcl
I
CL VCC/τEdge
τR = ½τEdge

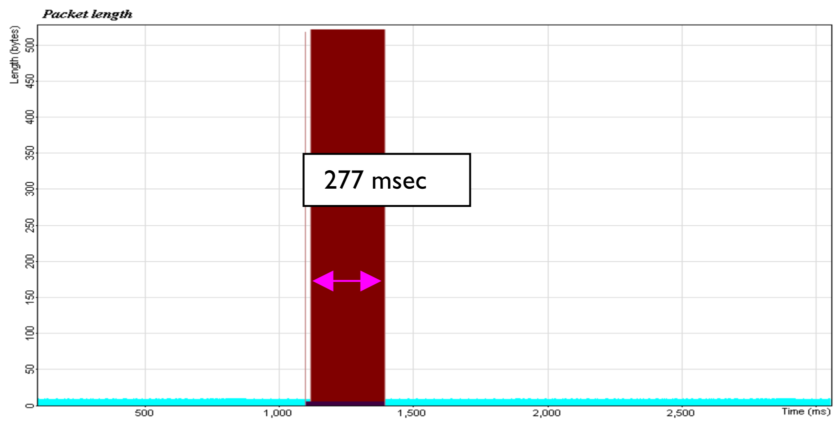
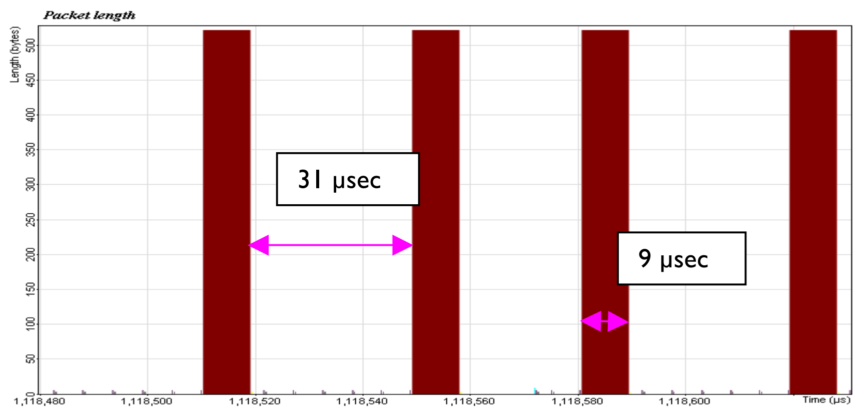
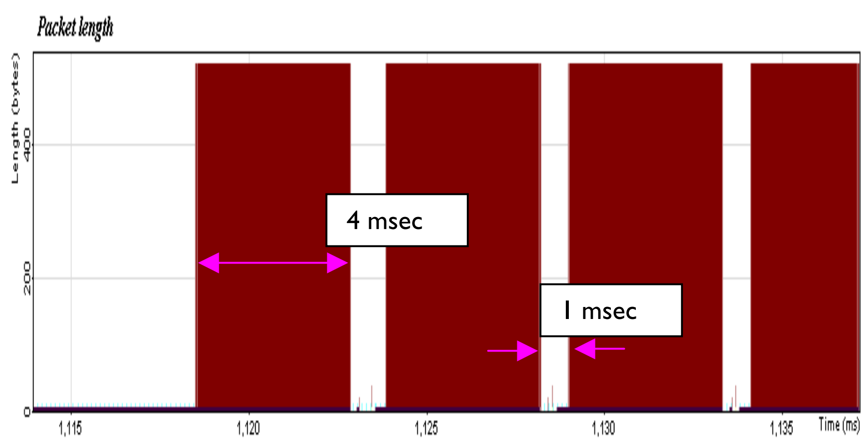
Appendix B: CATC traffic

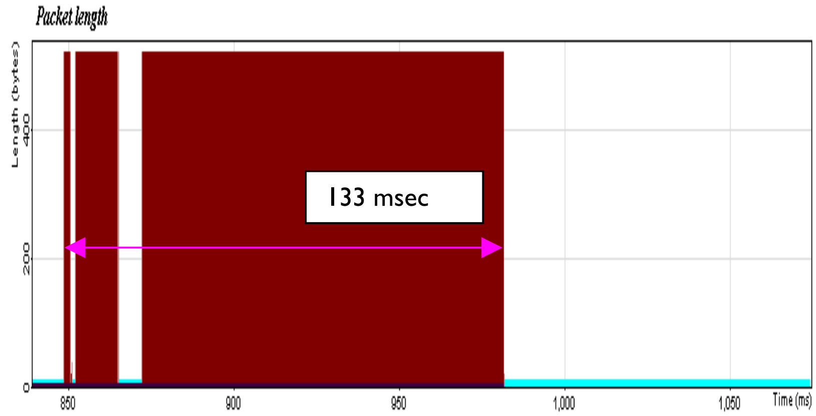
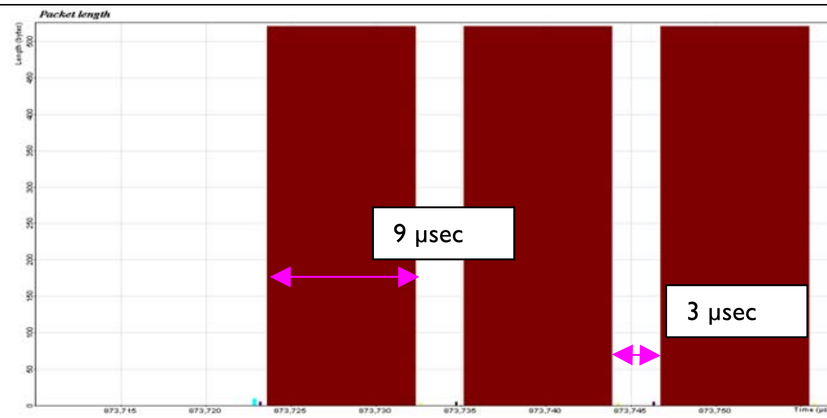
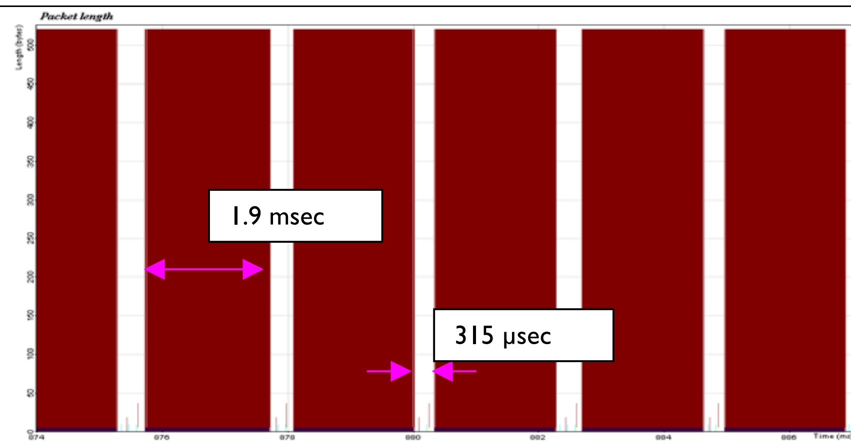
The following measurements are taken from the ISP1581 USB IDE hard drive with Maxtor 8 GB memory. An attempt to transfer 3.5 MB of random data from the hard disk to the PC is taken.

Data endpoint size = 64 bytes

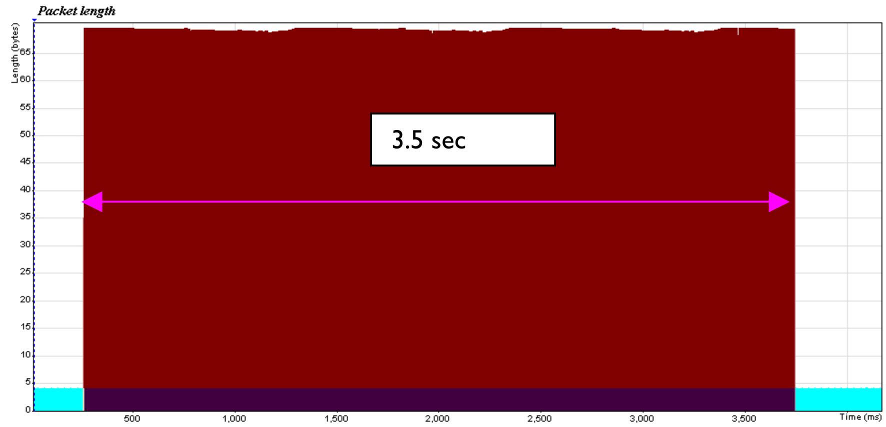
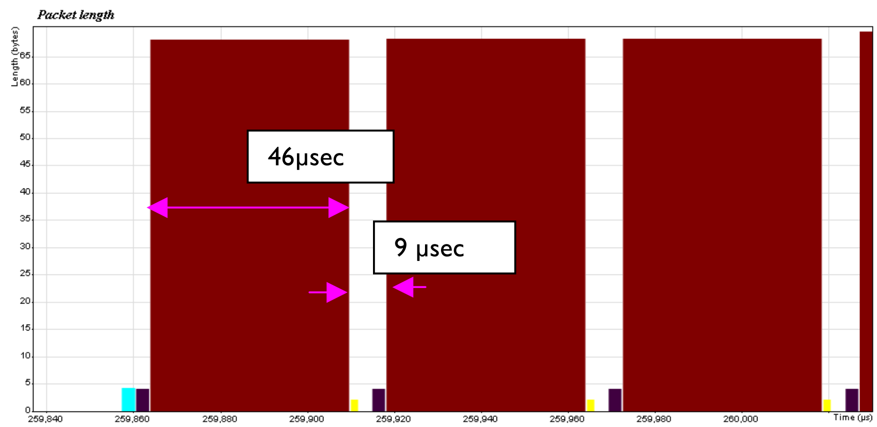
<table>
<tr><td colspan="2">The following data is collected from the ISP1581 USB hard disk in the full-speed mode.</td></tr>
<tr><td>The plot shows the timing for transferring 3.5 MB of data.</td><td>
</td></tr>
<tr><td>The plot shows the timing for transferring 512 bytes of data.</td><td>
</td></tr>
</table>

Data endpoint size = 512 bytes

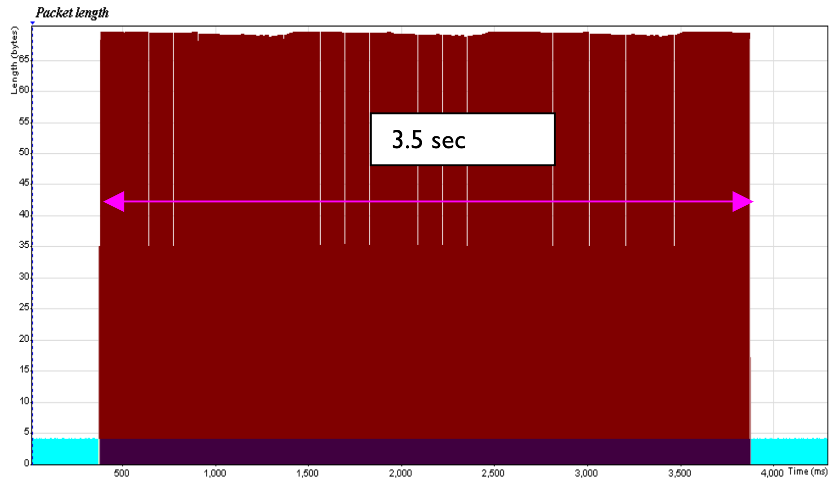
The following data is collected from the ISP1581 USB high-speed hard disk in the high-speed mode.	
The plot shows the timing for transferring 3.5 MB of data.	
The plot shows the timing for transferring 512 bytes of data.	
The plot shows the timing for transferring 65 KB of data.	

<table>
<tr><td colspan="2">The following data is collected from the Maxtor USB hard disk in the high-speed mode.</td></tr>
<tr><td>The plot shows the timing for transferring 3.5 MB of data.</td><td>
</td></tr>
<tr><td>The plot shows the timing for transferring 512 bytes of data.</td><td>
</td></tr>
<tr><td>The plot shows the timing for transferring 65 KB of data.</td><td>
</td></tr>
</table>

Data endpoint size = 64 bytes

The following data is collected from the Maxtor USB hard disk in the full-speed mode.	
The plot shows the timing for transferring 3.5 MB of data.	
The plot shows the timing for transferring 64 bytes of data.	

Data endpoint size = 64 bytes

<table>
<tr><td colspan="2">The following data is collected from the ISP1583 USB hard disk in the full-speed mode.</td></tr>
<tr><td>The plot shows the timing for transferring 3.5 MB of data.</td><td>
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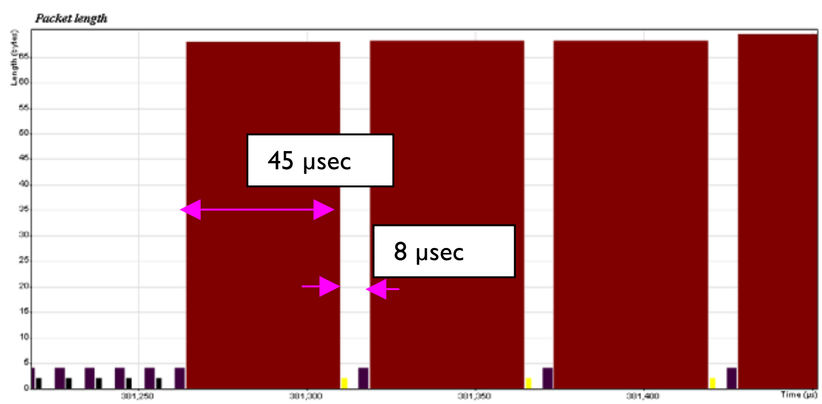
<tr><td>The plot shows the timing for transferring 64 bytes of data.</td><td>
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Data endpoint size = 512 bytes

<table>
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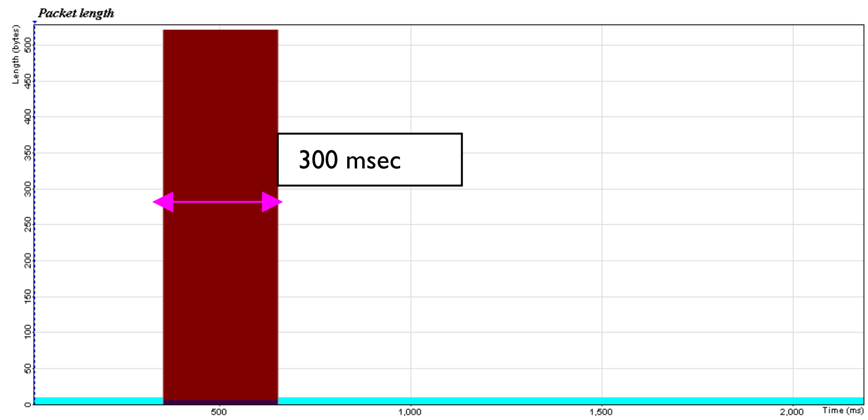
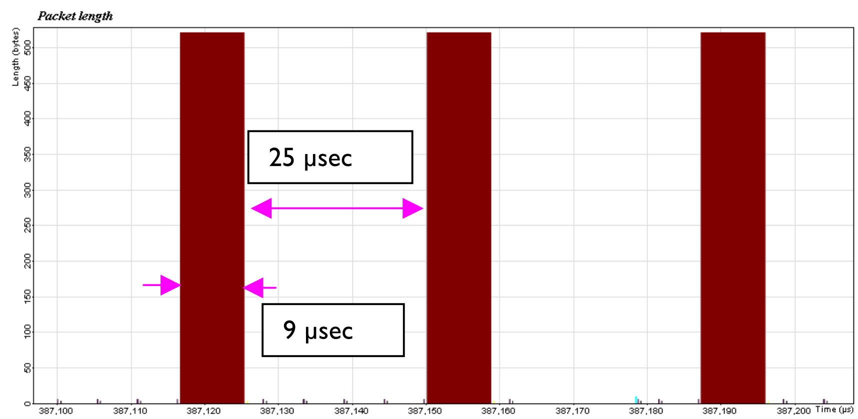
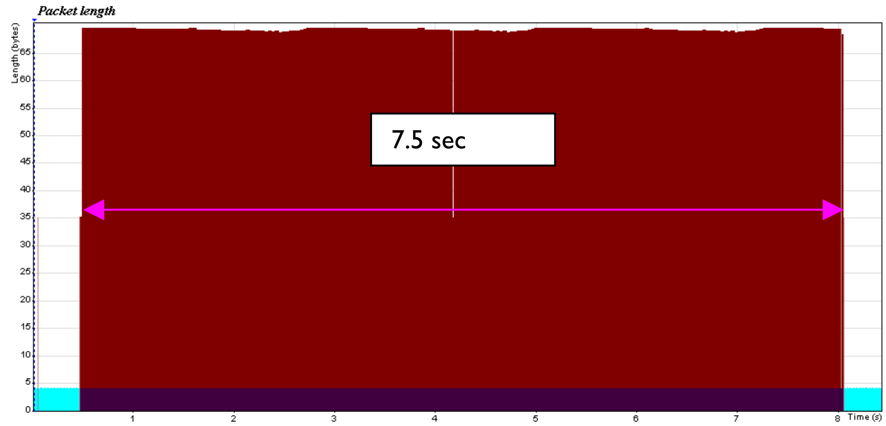
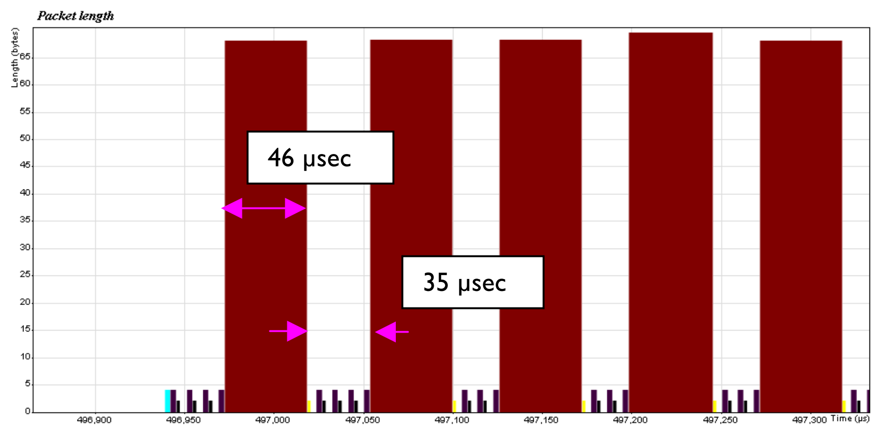
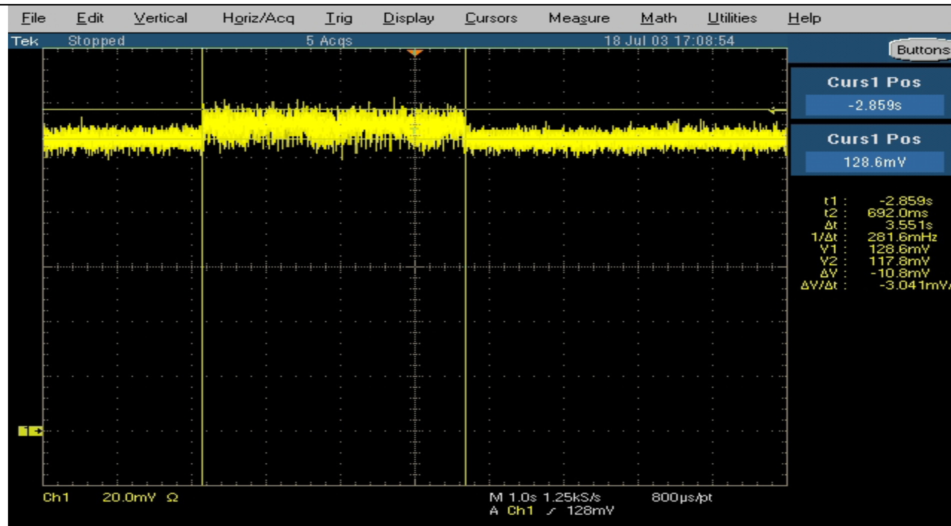
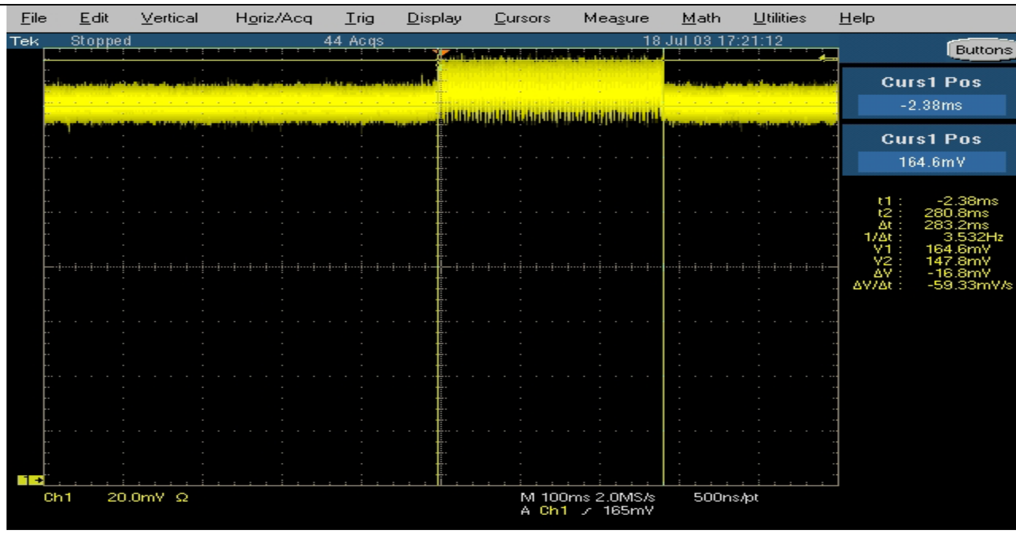
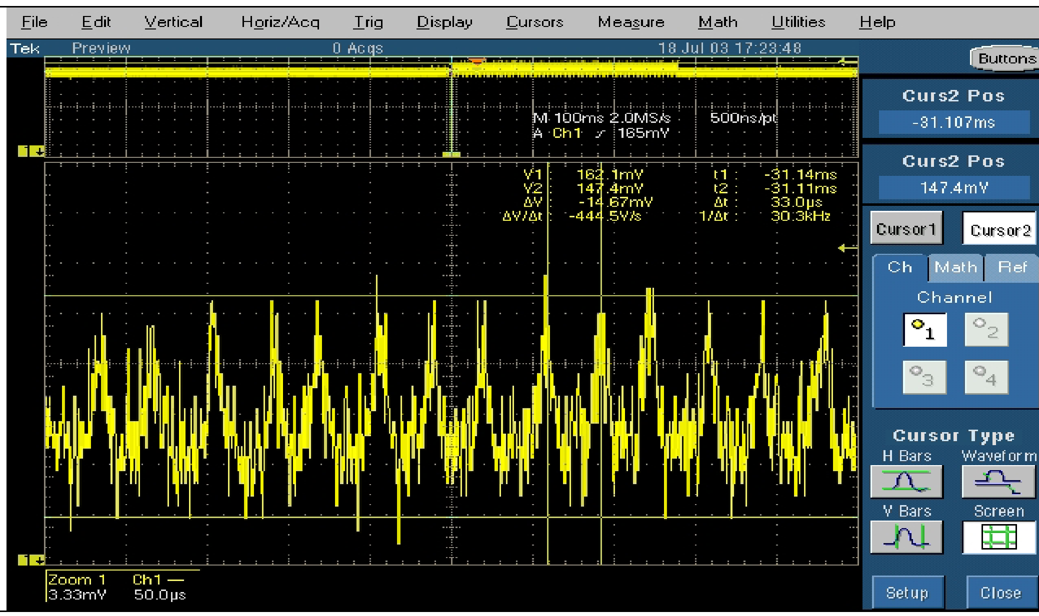
<tr><td>The plot shows the timing for transferring 3.5 MB of data.</td><td>
</td></tr>
<tr><td>The plot shows the timing for transferring 512 bytes of data.</td><td>
</td></tr>
</table>

Data endpoint size = 64 bytes.

The following data is collected from the PDIUSBD12 ThumbDrive in the full-speed mode.	
The plot shows the timing for transferring 3.5 MB of data.	
The plot shows the timing for transferring 64 bytes of data.	

Appendix C: Current measurements

The plot shows the full-speed read current: Idle = 117 mA, Transfer = 128 mA, a difference of 17 mA.		
The plot shows an enlarged view of the full-speed read current: Idle = 117 mA, Transfer = 128 mA.		

<table>
<tr><td></td><td></td></tr>
<tr><td>The plot shows the high-speed read current:
Idle = 147 mA,
Transfer = 164 mA, a difference of 17 mA</td><td>
</td></tr>
<tr><td>The plot shows an enlarged view of the high-speed read current:
Idle = 147 mA,
Transfer = 162 mA, a difference of 15 mA.</td><td>
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